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An Enhanced Static Compensator with DC-Link Voltage Shaping Method

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Abstract—This paper proposes a dc-link voltage shaping method for a cascaded H-bridge (CHB) static synchronous compensator (StatCom). A recently proposed low capacitance-StatCom system, which intentionally operates with large voltage ripples on the dc-link capacitors, offers the advantage of superior harmonic performance. However, the capacitor voltage ripples decrease when operating at below-rated reactive current, which removes the aforementioned harmonic performance benefit of this system. In addition, such harmonic performance benefit is only achieved in capacitive operation mode. In order to expand the operating region where advantageous voltage ripples are present, a new voltage shaping method is proposed. The proposed method uses a CHB multilevel converter coupled with simple dc-dc converters to shape voltage ripples on the dc-link capacitor regardless of its operating point. This is achieved by controlling the average current of the dc-dc converter using model predictive control (MPC). The concept is best applied to an enhanced StatCom, or E-StatCom, application in which the StatCom is integrated with either a renewable energy source or energy storage system. The operational principle of the proposed approach is validated via simulation and experimental results on a five-level single-phase CHB StatCom.

Index Terms—Cascaded H-bridge (CHB) converter, energy storage system (ESS), multilevel converter (MC), model predictive control (MPC), static synchronous compensator (StatCom).

I. INTRODUCTION

AS demands for renewable energy sources increase due to environmental issues, the application of flexible ac transmission systems (FACTS) for improving power flow control and grid voltage stability has attracted more attention

[1]. Among the FACTS devices, a static synchronous compensator (StatCom) is a device connected in parallel to transmission lines. It helps maintain stability of the grid and increases its power transfer capacity [2]. Many StatCom applications are used in medium-voltage and high-power systems, therefore the cascaded H-bridge multilevel converter (CHB-MC) is one of the most widely used converters, thanks to its benefits including: modularity, low switching loss, possibility to remove the low-frequency transformer, fast dynamics, and good harmonic performance [3].

Fig. 1 shows a single-phase CHB converter with N cells per phase-leg. The concept of utilizing a CHB-MC as a StatCom was introduced in [4]. Thereafter, many studies of StatComs based on the CHB have been conducted in the technical literature [5]–[16]. In conventional StatCom systems using CHB-MCs, voltage ripples on the dc capacitors are minimized as much as possible [5]–[16]. Each dc-link capacitor of the CHB converter is exposed to second order harmonics of fundamental frequency in instantaneous power, which translates into voltage ripples at the dc-side. As an approximate rule of thumb, the size of capacitors in the CHB converter are chosen to keep their voltage ripples to less than $\pm 10\%$ of the nominal dc voltage. Therefore, large capacitors, which increase the volume, cost, and weight of the system, are necessary to reduce magnitude of the low frequency ripples [17]–[21].

Recently, a low-capacitance StatCom (LC-StatCom) system has been proposed. The key concept of this system is that dc-link voltage ripples are considered as a positive aspect of StatCom operation which enhances overall performance [22]–[29]. Compared to the conventional CHB StatCom, large voltage ripples on the dc-link capacitors improve harmonic performance, decrease voltage stresses on the semiconductor devices, and reduce switching loss [23], [25], [28], [29]. These improvements are possible due to the lower average capacitor voltages and the resulting superior synthesized PWM voltages, where the output voltage of each H-bridge is shaped close to a sinusoidal waveform by the time-varying dc-link voltage.

Despite the advantages of the LC-StatCom, it is only able to operate with the nominal/maximum voltage ripple value on the capacitor when delivering rated capacitive current. As the ripple on the dc-link capacitor is a function of the current, when the current reduces below the rated value, the magnitude of the voltage ripple decreases which removes the

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abovementioned advantages of the LC-StatCom. Furthermore, a limited V-I operating capability due to phase mismatch between input and output voltage is the main disadvantage of the LC-StatCom [22]. In order to enlarge the V-I characteristic in inductive operation region, a passive reactive compensated LC-StatCom was proposed in [23]. Although this approach was able to facilitate operation throughout the full range of capacitive and inductive regions, additional thyristor switched series inductors are required.

In this paper, an active capacitor-voltage shaper is proposed to solve the previous shortcomings. It was shown that, in several previous papers, the H-bridge dc-capacitor voltage can be maintained with a desired constant dc value by using a simple dc-dc boost or buck converter cell in parallel with each dc-capacitor [30]-[32]. These previous power-decoupling approaches aimed to avoid large oscillation on each dc-link capacitor.

Fig. 1. One phase of a cascaded H-bridge StatCom with N cells.

Fig. 2. Enhanced StatCom integrated with ESS.

In contrast, this paper proposes intentionally increasing capacitor-voltage ripples, using the same circuit topology as previously proposed, to achieve the performance benefits seen in an LC-StatCom even when operating below rated current in either capacitive or inductive mode.

As distributed-generation systems and renewable energy sources such as photovoltaic and wind power generation become more prevalent, the integration of energy storage systems (ESSs) such as supercapacitors and batteries into StatCom devices has been investigated in recent years [33]-[38]. As shown in Fig. 2, this E-StatCom application typically requires a bidirectional dc-dc stage for energy storage integration, meaning that when the proposed concept is deployed in this application there is no need for any additional components. Therefore, the E-StatCom system is considered as the main application of the proposed concept. The operation of the proposed voltage shaper concept is validated via simulations and experimental results on a five-level 1-kVA single-phase CHB-based E-StatCom. Comparative results between the previously proposed LC-StatCom and proposed E-StatCom are also provided via both simulations and hardware.

The rest of this paper is organized as follows: Section II provides a brief background of the LC-StatCom, Section III introduces the proposed active capacitor voltage shaping concept, and Section IV provides simulation and experimental results for the proposed CHB-StatCom. Finally, conclusions are provided in Section V.

II. LC-STATCOM BACKGROUND

A. Topology

As mentioned in the previous section, the LC-StatCom operates with large cluster voltage ripple, where cluster voltage is defined as the sum of the capacitor voltages in a phase-leg ($v_{c-1} + v_{c-2} + \dots + v_{c-n}$).

Fig. 3 shows that the LC-StatCom is able to achieve large capacitor voltage ripples when the system operates with rated current (left side of Fig. 3). However, as the current reduces below the rated current, the magnitude of voltage ripple on the capacitors decreases (from left to right).

Fig. 4 shows a comparison between operational waveforms of the LC-StatCom in capacitive and inductive modes. In capacitive mode, the cluster voltage has the same phase angle as the absolute value of the grid voltage. As a result, the output voltage of the converter is close to a sinusoidal waveform. However, the cluster voltage is 180 degrees in contrast to the grid voltage in inductive mode, which acts to reduce output waveform quality, as shown in Fig. 4 (b). Therefore, the harmonic performance of inductive operation with large ripple is inferior to that of the capacitive region [29].

This work aims to shape the cluster voltage to be consistently large to obtain a high harmonic performance not only in capacitive mode but also in low current conditions and in inductive mode by utilizing a dc-dc converter.

Fig. 3. Operating principle of LC-StatCom with fixed V_{C-max} .

Fig. 4. Operation comparison in LC-StatCom between (a) capacitive mode and (b) inductive mode.

B. Desired Capacitor Voltage Waveform.

This section provides an expression for the capacitor voltage as a function of the grid voltages and converter current. Since a three-phase configuration is simply an extension of three individual single-phase converters, for the rest of this paper, a single-phase converter is considered without loss of generality. Using the notation and sign convention of Fig. 5, the dc-link voltage dynamic in absence of the voltage shaping stage (i.e., $i_{b-j} = 0$) is defined as:

$$C \frac{dv_{c-j}}{dt} = i_{c-j} = -i_j \quad (1)$$

where subscript $j \in \{1, 2, \dots, N\}$ represents the j^{th} cell and N is the number of cells. C is the equivalent capacitance of each cell. v_{c-j} and i_{c-j} represent the voltage and current of the j^{th} capacitor and i_j is the input current on the j^{th} H-bridge inverter cell. The instantaneous power on the dc-side can be expressed by:

$$v_c i_j = -v_c i_{c-j} = v_{inv-j} i_g \quad (2)$$

where output voltage of the j^{th} inverter is given by v_{inv-j}

An expression for the capacitor voltage can be derived by assuming the total output voltage of converter is:

$$v_{inv} = \hat{v}_{inv} \sin(\omega t + \alpha) \quad (3)$$

the current is harmonic free and purely reactive:

$$i_g = \hat{i}_g \sin(\omega t + \varphi) \quad (4)$$

Fig. 5. Proposed active capacitor-voltage shaper circuit.

where ω is the angular frequency of the grid voltage, $\hat{v}_{inv}$ and α are, respectively, the instantaneous magnitude and phase angle difference with respect to the grid voltage in a phase-leg. $\hat{i}_g$ and φ represent the instantaneous current magnitude and phase angle with respect to the grid voltage, respectively. The angle φ depends on the operation mode, which is ideally $-\pi/2$ rad in capacitive mode, whereas $\pi/2$ rad in inductive mode since the grid current is defined flowing out of the converter. The general expression of the capacitor voltage is derived and shown below [22]:

$$v_c(t) = \sqrt{V_{c-max}^2 - \frac{\hat{v}_{inv} \hat{i}_g}{2N\omega C} + \frac{\hat{v}_{inv} \hat{i}_g}{2N\omega C} \sin(2\omega t + \alpha + \varphi)} \quad (5)$$

where V_{c-max}^2 is the square of the maximum capacitor voltage. The expression for the capacitor voltage shown in (5) will be used in the next section to design a current reference for the dc-dc converter that shapes the dc-link voltage as desired.

III. PROPOSED CHB-STATCOM

A. Basics of Proposed Concept

The LC-StatCom will obtain the maximum capacitor voltage ripple when operating with rated capacitive current. It can take full advantage of the large ripple to improve its performance in terms of output waveform spectra and switching loss [27], [29]. However, in practice, the LC-StatCom will often either work with below rated currents or inductive current, where it will not be able to take benefits from large voltage ripple [27]-[29]. The proposed active shaping circuit solution is shown in Fig. 5. It aims to overcome this issue by making the CHB-StatCom more adaptable to the light loading condition. From Fig. 5, and using Kirchhoff's current law on the capacitor, the equivalent j^{th} capacitor voltage value can be expressed by:

$$v_{c-j} = \frac{1}{C} \int i_{c-j} dt = \frac{1}{C} \int i_{b-j} - i_j dt \quad (6)$$

where i_{b-j} is the current injected from the j^{th} dc-dc cell. As can be seen from (6), the voltage ripple of the dc capacitor can be adjusted by controlling the magnitude and/or the phase angle of the current injected by the dc-dc cell. From (6), considering no losses in the H-bridge cells and that the dc-link capacitor voltage must be regulated to a desired waveform v_c^* , the

ac-term of the dc-dc converter reference current can be defined as:

$$i_{b(ac)-j}^* = C \frac{dv_c^*}{dt} + \frac{v_{inv-j}^* i_g}{v_{c-j}} \quad (7)$$

where v_{inv-j}^* is the output reference voltage of the j^{th} H-bridge inverter, which is obtained from the capacitor voltage balancing controller based on phase-shifted carrier-PWM with individual voltage loops as in [10]. v_c^* is the desired capacitor voltage to be shaped. Here, the reference is defined based on pure capacitive mode (best possible harmonic performance scenario [29]), which is given by:

$$v_c^*(t) = \sqrt{V_{c-max}^2 - \frac{\hat{V}_{inv-n} \hat{I}_{g-n}}{2N\omega C} - \frac{\hat{V}_{inv-n} \hat{I}_{g-n}}{2N\omega C} \cos(2\omega t)}$$

where $\hat{V}_{inv-n}$ and $\hat{I}_{g-n}$ are the nominal amplitudes of the total inverter output voltage and grid current, respectively. $\hat{I}_{g-n}$ is chosen as the nominal amplitude of the reactive current, which is represented by $\hat{I}_{q-n}$. Then, $\hat{V}_{inv-n}$ is chosen as $\hat{V}_{inv-n} = \hat{V}_{g-n} + X_L \hat{I}_{q-n}$ where $\hat{V}_{g-n}$ is the nominal amplitude of the grid voltage and $X_L = \omega L$ is the inductive reactance of the ac-side filter L . The d component of the grid current, which is provided by the outer control loop to compensate the overall energy balance, is reflected onto the dc-side disturbing the dc-link capacitor voltage. The aim of the dc-dc converter is to compensate for this, which is achieved by adding the dc-link current to the ideal current in (7) that shapes the capacitor voltage in the desired way. Therefore, the reference for the output dc-dc converter current is given by substituting (8) into (7). The final current reference of the j^{th} dc-dc converter to shape the capacitor voltage is given by:

$$i_{b(ac)-j}^* = \frac{(\hat{V}_{g-n} + X_L \hat{I}_{q-n}) \hat{I}_{q-n} \sin(2\omega t)}{2Nv_c^*} + \frac{v_{inv-j}^* i_g}{v_{c-j}} \quad (9)$$

B. Control System of Proposed StatCom

From a hardware perspective, except for the dc-dc converters, the proposed StatCom is very similar to the conventional LC-StatCom. Thus, previously proposed control schemes [22] can be utilized to control the dc-ac side of the converter. Figs. 6 and 7 depict an overall view of the proposed control system for the dc-ac CHB and dc-dc section, respectively. Salient features of the proposed control are discussed below:

1) The active current reference i_d^* is provided by the outer voltage control loop in conventional StatCom systems. In order to compensate active power losses and balance the capacitor voltages in the proposed concept, traditional controllers were used, however, the value that these controllers act upon should be total cell energy and not just energy associated with v_b to determine i_d^* .

An error between the square of the total dc input voltage reference and measured voltage is fed to the PI controller

through a moving average filter (MAF) to reduce the voltage ripple (overall outer voltage controller)

2) A conventional dead-beat current controller is used to track i_g^* (current controller).

3) PSC-PWM with individual PI controllers is applied to determine the duty cycle reference of each H-bridge cell so that input voltages of the dc-dc converters are balanced (individual balancing controller).

4) In order to maximize cluster voltage independently from the operating point (i.e., even at light loading condition), a desired injected current reference for the ac-term is calculated by (9). In addition, an offset term, which is the dc-component to compensate losses in the dc-dc converter, was added to the ac current reference, which otherwise causes a drift/deviation in cluster voltage. Here, also a MAF is used (offset compensator). The reference for the dc-offset component is defined as in (10), which allows a peak regulation of the dc-link voltage considering rated operation.

$$V_{c(dc),n}^{2*} = V_{c-max}^2 - \frac{(\hat{V}_{g-n} + X_L \hat{I}_{q-n}) \hat{I}_{q-n}}{2N\omega C} \quad (10)$$

5) A direct model predictive control (MPC) scheme is utilized to track the current reference of each buck converter that shapes the corresponding dc-link capacitor voltage. The continuous-time model of the buck converter under continuous conduction mode is:

$$\frac{di_{b-j}(t)}{dt} = -\frac{v_{c-j}(t)}{L_b} + S_{b-j}(t) \frac{v_{b-j}(t)}{L_b} \quad (11)$$

$$S_{b-j} = \begin{cases} 1, & \text{switch is on.} \\ 0, & \text{switch is off.} \end{cases}$$

Then, the approximated discrete model of the buck converter is given in (12):

$$i_{b-j}(k+1) = i_{b-j}(k) - \frac{v_{c-j}(k)T_s}{L_b} + S_{b-j}(k) \frac{v_{b-j}(k)T_s}{L_b} \quad (12)$$

where T_s is the control/sampling time period.

In direct MPC both of the possible switching combinations are tested then the one that minimizes the cost function is selected. A standard cost function of predictive controller that minimizes the tracking error of the dc-dc inductor current is chosen as:

$$J(k) = \left(i_{b-j}^*(k+1) - i_{b-j}(k+1) \right)^2 \quad (13)$$

The MPC algorithm is presented in Fig 8 and its operating process is demonstrated as follow. First, all parameters needed to predict a current reference for the next timestep are measured. Second, the current reference for the next sampling instant is calculated with given switching states through (12). Third, the cost function is evaluated for each prediction using (13), then the switching state is selected that minimizes the cost function. Finally, the new switching state is applied to the dc-dc converter.

Fig. 6. Control scheme for the dc-ac stage of the proposed E-StatCom: outer voltage controller, current controller, voltage balancing controller.

Fig. 7. Proposed control scheme for the j -th dc-dc converter voltage shaper circuit.

Fig. 8. MPC algorithm flowchart for current control in dc-dc converter

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. Hardware Operation of Proposed CHB-StatCom

A single-phase five-level 1-kVA CHB converter was constructed to verify the proposed CHB-StatCom system experimentally. The photograph and circuit diagram of the hardware setup are shown in Figs. 9 and 10 respectively, with associated experimental parameters given in Table I. The base impedance to normalize L is derived using nominal grid voltage 110 V and nominal 540 VA power rating of the converter. With given base impedance 22.3 Ω , the filter inductor is chosen by 0.07 p.u. which is 5 mH. The capacitor value for each H-bridge cell C_j with specific maximum ripple is selected as follows [27]:

$$C_j = \frac{\hat{V}_{g-n} \hat{I}_{q-n}}{\omega N r (2-r) V_{c-max}^2} \quad (14)$$

where subscripts n represents nominal parameters and r is the maximum voltage ripple. For reaching 70% maximum ripple capacitance value is calculated as 190 μF per each H-bridge. In the practical hardware setup, a 180 μF capacitor value is used. The inductor value of the dc-dc buck converter is calculated by:

Fig. 9. Experimental setup of a single-phase five-level CHB converter StatCom.

Fig. 10. Circuit diagram of the simulations and experiments of the proposed CHB-StatCom with the voltage shaper buck cell.

TABLE I
EXPERIMENTAL PARAMETERS OF THE PROPOSED CHB-StatCom

Symbol	Quantity	Values
$\hat{V}_{g-n}$	Nominal amplitude of grid voltage	$110\sqrt{2}$ V
$\hat{I}_{q-n}$	Nominal amplitude of reactive current	7 A
V_{c-max}	Maximum voltage H-bridge capacitors	100 V
$V_{c(dc),n}$	Nominal dc-component in the dc-link capacitor	70 V
V_{b-n}	Nominal dc-component in the auxiliary input capacitor	160 V
C_j	Capacitance: H-bridge capacitors	180 μ F
C_{b-j}	Capacitance: dc-dc converters	1.44 mF
L	Inductance: H-bridge filter	5 mH
L_{b-j}	Inductance: dc-dc converter	5 mH
f_s	Switching frequency	15 kHz
f_g	Grid fundamental frequency	50 Hz
R	Filter inductor series resistance	0.3 Ω
S	Converter nominal power	540 VA
N	Number of H-bridge cells	2

$$L_{b-j} = \frac{V_{b-n} - V_{c(dc)-n}}{f_s \Delta i_{b-j}} D \quad (15)$$

where D is the duty ratio at the nominal operation point of the buck converter and Δi_{b-j} is the increment component of the inductor current. By considering small current ripple, here ± 0.5 A, on the buck converter, the inductor value for the buck converter is calculated as 5.25 mH, which is selected 5 mH in practical experimental setup.

Two IMPERIX PEH2015 H-bridge converters were connected in series to form the five-level converter. Two IMPERIX PEH4010 H-bridge converters were connected to each PEH2015 module in parallel as dc-dc converters using one leg only as a buck converter. In this work, relatively large auxiliary capacitors (1.44 mF) are used at the input to each buck converter, which emulates an E-StatCom supercapacitor application. The single-phase grid voltage, which is 110V, is supplied by a CINERGIA grid simulator. All other control systems were implemented using an IMPERIX BOOMBOX control board connected to both H-bridges and dc-dc modules by optical link.

Steady state operation of the proposed StatCom system with the voltage shaper when delivering full capacitive load is shown in Fig. 11. Fig. 12 shows operation of the StatCom without voltage shaper at the same reactive power condition. There are no differences in terms of the voltage ripples on the input capacitors between the two cases, in which both cases have large ripples, approximately 120 V, and ac output voltages close to sinusoidal shown in Figs. 11 (a) and 12 (a).

The next experiment studies operation under inductive mode where the reactive current references are 1.8 A and 7 A. Fig. 13 shows that the proposed StatCom is able to operate with large ripples, approximately 120 V, in phase with grid voltage when delivering 1.8 A inductive reference current. The voltage shaper is in operation by injecting currents (i_b) provided by the voltage shaper controller. Operation of the conventional LC-StatCom is shown in Fig. 14. The converter is supplying 1.8 A inductive current shown in Fig. 14 (b), where the voltage shaper is not operating. It is worth noting that the PWM output voltage is no longer close to a sinusoidal waveform, but close to conventional PWM output voltage (Fig. 14 (a)).

Moreover, if the operating point goes up to more than 1.8 A inductive current, the converter is not able to work without voltage shaper in inductive mode because the capacitor voltage ripple would be increased, and the converter would deviate from an implementable operational point (cluster voltage overlaps desired output voltage to be generated since the capacitor voltage is shifted by 180 degrees with respect to the grid voltage and output converter voltage in inductive mode). Therefore, it is essential to maintain a higher reference voltage for capacitor voltages in conventional StatCom and LC-StatCom.

However, as can be seen in Fig. 15 (a), the proposed CHB-StatCom was able to operate with large voltage ripples even under full inductive mode while the capacitor voltage has the same phase as the grid voltage, as opposed to the conventional StatCom system.

Fig. 11. Experimental operation of proposed StatCom when delivering its nominal capacitive current $i_q^* = -7$ A with shaper operation. (a) dc-ac stage and (b) dc-dc stage with grid voltage and current.

Fig. 13. Experimental operation of proposed StatCom when $i_q^* = 1.8$ A with shaper operation under inductive mode. (a) dc-ac stage and (b) dc-dc stage with grid voltage and current.

Fig. 12. Experimental operation of conventional LC-StatCom when delivering its nominal capacitive current $i_q^* = -7$ A without voltage shaper. (a) dc-ac stage and (b) dc-dc stage with grid voltage and current.

Fig. 14. Experimental operation of conventional LC-StatCom when $i_q^* = 1.8$ A without shaper operation under inductive mode. (a) dc-ac stage and (b) dc-dc stage with grid voltage and current.

Fig. 15. Experimental operation of proposed StatCom when $i_q^* = 7$ A with voltage shaper under full inductive mode. (a) dc-ac stage and (b) dc-dc stage with grid voltage and current.

Fig. 17. Experimental operation of proposed StatCom when the reactive current reference changes from full capacitive ($i_q^* = -7$ A) to full inductive ($i_q^* = 7$ A) at $t = 0.03$. (a) dc-ac stage and (b) dc-dc stage with grid voltage and current.

Fig. 16. Experimental operation of proposed StatCom when the reactive current reference changes from full inductive ($i_q^* = 7$ A) to full capacitive ($i_q^* = -7$ A) at $t = 0.03$. (a) dc-ac stage and (b) dc-dc stage with grid voltage and current.

In Figs. 16 and 17, fast transient step change cases are investigated, in which the reactive current reference changes from full inductive ($I_{q-ref} = 7$ A) to full capacitive ($I_{q-ref} = -7$ A) and viceversa, respectively. The reactive power reference is changed at $t = 0.03$ s in both cases and the results demonstrate the capability of the proposed StatCom system to shape capacitor voltages in both inductive and capacitive operating regions. Furthermore, stable operation of the system when moving from inductive to capacitive region and viceversa can be seen in Fig. 16 and 17.

B. THD Analysis

Harmonic analysis on a five-level single-phase CHB-converter was conducted to verify total harmonic distortion (THD) improvement of the proposed CHB-StatCom compared to the conventional LC-StatCom. The simulation results of harmonic analysis of the output voltages for the conventional LC-StatCom and proposed CHB-StatCom at 0.3 p.u. for both the capacitive and inductive modes with 10 mH filter inductor are demonstrated in Figs. 18 and 19, respectively. The output voltage's THD in capacitive mode are 43.3% (conventional) and 29.2% (proposed CHB-StatCom), while the THD in inductive mode were changed from 48% (conventional) to 33.6% (proposed CHB-StatCom). It is noted that the difference in THD between inductive and capacitive mode in Fig. 19 is predominantly due to the difference in fundamental frequency magnitude (148.7 V vs 161.6 V, respectively). This improvement is a result of shaping the cluster voltage of the proposed CHB-converter in phase with grid voltage so that output voltage of the CHB converter is close to a sinusoidal waveform.

Fig. 18. Simulation results. Harmonic spectrum of the output voltage of the conventional LC-StatCom delivering 0.3 p. u. reactive power: (a) capacitive mode and (b) inductive mode.

Fig. 19. Simulation results. Harmonic spectrum of the output voltage of the proposed CHB-StatCom delivering 0.3 p. u. reactive power: (a) capacitive mode and (b) inductive mode.

The harmonic analysis results of the output current are also demonstrated. Fig. 20. (a) and 21. (a) show the current THD of the conventional LC-StatCom and proposed CHB-StatCom in capacitive mode are 16.5% and 7.9%, respectively. The current THD of the conventional LC-StatCom in inductive mode is 18.2%, as shown in Fig. 20. (b), which is higher than the result in the proposed CHB-StatCom of 9.7% as shown in Fig. 21. (b). The low harmonic performance in the conventional LC-StatCom at 0.3 p. u. in capacitive mode, due to lower voltage ripple, is compensated by the proposed voltage shaping method. In addition, current THD in inductive mode has improved without adding extra inductors.

Fig. 22 shows the harmonic spectrum obtained experimentally. As can be seen, the output voltages and spectrums of the proposed CHB-StatCom in capacitive and inductive modes are similar to each other, as well as similar to those of simulation (Fig. 19) showing THD 30.7% and 35.4% in each mode.

Fig. 20. Simulation results. Harmonic spectrum of the output current of the conventional LC-StatCom delivering 0.3 p. u. reactive power: (a) capacitive mode and (b) inductive mode.

Fig. 21. Simulation results. Harmonic spectrum of the output current of the proposed CHB-StatCom delivering 0.3 p. u. reactive power: (a) capacitive mode and (b) inductive mode.

Fig. 22. Experimental results. Harmonic spectrum of the output voltage of the proposed CHB-StatCom: (a) full capacitive mode and (b) full inductive mode.

C. Loss Analysis

In this section, simulations are designed to compare losses for a conventional CHB E-StatCom and the proposed CHB E-StatCom. A 5 and 10-cell CHB E-StatCom with parameters given in Table II are simulated in MATLAB/Simulink to quantify the losses. With 5 cells the system connection voltage is 6kV, for 10 cells the connection voltage is 12kV. It is noted that the dc-link capacitors for the conventional E-StatCom are assumed large enough that voltage ripple is negligible. In the following result, 5SHY 35L4522 IGCT switches (4500V, 2100A (rms current)) with 5SDF 20L4520 anti-parallel fast recovery diodes (4500V, 1970A) are used for the H-bridge side. The dc-dc side uses CMH1200DC-34S SiC hybrid IGBT switches (1700V, 1200A), with two devices assumed connected in series to meet the required blocking voltage. For calculating losses, datasheet values are linearly scaled using instantaneous switch current and dc-link voltage magnitude. Also, I-V curves for junction temperature of 125 degrees were interpolated to provide a more accurate loss analysis.

The simulation results present total semiconductor losses including both switching and conduction loss on a per-cell basis. Fig. 23 demonstrates that total loss increases moving from full capacitive to full inductive mode when utilizing the proposed shaper concept. These increased losses are a result of intentionally injecting current from the dc-dc stage to maintain large voltage ripple on the dc-link capacitors. However, the results show that these increases can be minimized by adjusting dc-link capacitance, as this affects the required injected dc-dc current magnitude. For instance, the simulation results show loss analysis for use of a 3.4 mF and 1.13 mF dc-link capacitance.

Each column of the graph splits into two subsections that upper side is the total losses from dc-dc converter and bottom side is the total losses produced by H-bridge for the proposed CHB-E-StatCom system. It can be seen that the ratio of the dc-dc side's losses respected to total losses is relatively high at inductive mode, as shaper operates, which result in higher total losses at inductive mode.

Using the proposed shaping concept increases the total loss 32% compared to the conventional system in full inductive mode (2000A) with 3.4 mF, while it increases 7% with 1.13 mF as shown in Fig. 23 (assuming a 10-cell system). The total loss with shaper in full capacitive mode (-2000A) decreases 29% compared to the conventional system with 3.4 mF, while it decreases 16% with 1.13 mF as shown in Fig. 23 (assuming a 10-cell system).

Additionally, the number of the H-bridge cells has an effect on the total losses produced by each cell. This is due to the assumption that with fewer cells the H-bridge switching frequency must be increased to maintain the harmonic performance. Fig. 24 shows the loss comparison with a configuration of 5-cells, in this result, the losses associated with inductive mode are slightly decreased but significantly decreased in capacitive mode.

The effect on losses of simultaneously supplying active and reactive power to the grid can be seen in Fig. 25. Again, the losses are decreased slightly in inductive mode while the losses are significantly decreased in capacitive mode.

TABLE II
SIMULATION PARAMETERS OF THE PROPOSED CHB-STATCOM

Symbol	Quantity	Values
$\hat{V}_{g-n}$	Nominal amplitude of grid voltage	$6000\sqrt{2} \text{ V} / 12000\sqrt{2} \text{ V}$
$\hat{i}_{q-n}$	Nominal amplitude of reactive current	2 kA
V_{c-max}	Maximum voltage H-bridge capacitors	1.9 kV
V_{b-n}	Nominal dc-component in the auxiliary input capacitor	1.9 kV
C_i	Capacitance: H-bridge capacitors	3.4 mF / 1.13 mF
C_{b-d}	Capacitance: dc-dc converters	260 F / 520 F
L	Inductance: H-bridge filter	0.1 mH
L_{b-d}	Inductance: dc-dc converter	0.5 mH
f_s	Switching frequency per H-bridge	1 kHz / 500 Hz
f_g	Grid fundamental frequency	50 Hz
R	Filter inductor series resistance	0.01 Ω
S	Converter nominal power	8.5 MVA / 17 MVA
N	Number of H-bridge cells	5 / 10

Fig. 23. Losses distribution on a cell for a conventional StatCom and proposed CHB-StatCom with 10-cells.

Fig. 24. Losses distribution on a cell for a conventional StatCom and proposed CHB-StatCom with 5-cells.

Fig. 25. Losses distribution on a cell for a conventional StatCom and proposed CHB-StatCom with 5-cells during active power injecting to the grid (1000A).

In summary, the presented loss analysis demonstrates that shaping capacitor voltages in inductive mode, when using a hard-switched boost converter, is difficult to justify with high cell numbers from a loss analysis perspective (the concept could still be justified in terms of superior harmonic performance and reducing dc-link capacitance values). However, in capacitive mode, the shaper concept can simultaneously provide superior efficiency and harmonic performance.

V. CONCLUSION

Operation of the proposed voltage shaper for the CHB-StatCom application is investigated. Capacitor voltages were able to be maintained at their maximum even in light loading conditions and inductive mode, which offers superior harmonic performance. As can be seen from simulation and experimental results, an improvement of THD in inductive mode was approximately 50%. Furthermore, capacitor voltages were shaped in the same phase angle with H-bridge output and grid voltage when providing inductive power to the grid as opposed to the conventional LC-StatCom. This result allows removal of the additional series inductors from the conventional LC-StatCom by using dc-dc converters as the voltage shaper which, therefore, is suitable for an E-StatCom application.

REFERENCES

- [1] M. Hasheminamin, V. G. Agelidis, V. Salehi, R. Teodorescu, and B. Hredzak, "Index-based assessment of voltage rise and reverse power flow phenomena in a distribution feeder under high PV penetration," *IEEE Journ. of Photovoltaics*, vol. 5, no. 4, pp. 1158–1168, Jul. 2015.
- [2] C. Schauder, M. Gernhardt, E. Stacey, T. Lemak, L. Gyugyi, T.W. Cease, and A. Edris "Development of a ± 100 MVAR static condenser for voltage control of transmission systems," *IEEE Trans. Power Del.*, vol. 10, no. 3, Jul. 1995.
- [3] J. S. Lai and F. Z. Peng, "Multilevel converters—a new breed of power converters," *IEEE Trans. Ind. Appl.*, vol. 32, no. 3, pp. 509–517, May/Jun. 1996.
- [4] Y. Liang and C. O. Nwankpa, "A new type of StatCom based on cascading voltage-source inverters with phase-shifted unipolar SPWM," *IEEE Trans. Ind. Appl.*, vol. 35, no. 5, pp. 1118–1123, Sep./Oct. 1999.
- [5] Y. Li and B. Wu, "A novel DC voltage detection technique in the CHB inverter-based STATCOM," *IEEE Trans. Power Del.*, vol. 23, no. 3, pp. 1613–1619, Jul. 2008.
- [6] L. K. Haw, M. S. A. Dahidah, and H. A. F. Almurib, "SHE-PWM cascaded multilevel inverter with adjustable DC voltage levels control for STATCOM applications," *IEEE Trans. Power Electron.*, vol. 29, no. 12, pp. 6433–6444, Dec. 2014.
- [7] R. Xu, Y. Yu, R. Yang, G. Wang, D. Xu, B. Li, and S. Sui, "A novel control method for transformerless H-bridge cascaded STATCOM with star configuration," *IEEE Trans. Power Electron.*, vol. 30, no. 3, pp. 1189–1202, Mar. 2015.
- [8] H. C. Chen, P. H. Wu, C. T. Lee, C. W. Wang, C. H. Yang and P. T. Cheng, "A flexible DC voltage balancing control based on the power flow management for star-connected cascaded H-bridge converter," *IEEE Trans. Ind. Appl.*, vol. 52, no. 6, pp. 4946–4954, Nov.-Dec. 2016.
- [9] Y. Zhang, X. Wu, X. Yuan, Y. Wang and P. Dai, "Fast model predictive control for multilevel cascaded H-bridge STATCOM with polynomial computation time," *IEEE Trans. Ind. Electron.*, vol. 63, no. 8, pp. 5231–5243, Aug. 2016.
- [10] G. Farivar, B. Hredzak and V. G. Agelidis, "Decoupled control system for cascaded H-bridge multilevel converter based STATCOM," *IEEE Trans. Ind. Electron.*, vol. 63, no. 1, pp. 322–331, Jan. 2016.
- [11] D. Lu, J. Wang, J. Yao, S. Wang, J. Zhu, H. Hu, L. Zhang, "Clustered voltage balancing mechanism and its control strategy for star-connected cascaded H-bridge STATCOM," *IEEE Trans. Ind. Electron.*, vol. 64, no. 10, pp. 7626–7633, Apr. 2017.
- [12] H. C. Chen and P. T. Cheng, "A DC bus voltage balancing technique for the cascaded H-bridge STATCOM with improved reliability under grid faults," *IEEE Trans. Ind. Appl.*, vol. 53, no. 2, pp. 1263–1270, Mar.-Apr. 2017.
- [13] C. D. Townsend, T. J. Summers, and R. E. Betz, "Multigoal heuristic model predictive control technique applied to a cascaded H-bridge StatCom," *IEEE Trans. Power Electron.*, vol. 27, no. 3, pp. 1191–1200, Mar. 2012.
- [14] C. D. Townsend, T. J. Summers, J. Vodden, A. J. Watson, R. E. Betz, and J. C. Clare, "Optimization of switching losses and capacitor voltage ripple using model predictive control of a cascaded H-bridge multilevel StatCom," *IEEE Trans. Power Electron.*, vol. 28, no. 7, pp. 3077–3087, Jul. 2013.
- [15] C. D. Townsend, T. J. Summers, and R. E. Betz, "Issues on the harmonic performance of phase-shifted modulation strategies for a cascaded Hbridge StatCom," *IEEE Trans. Ind. Electron.*, vol. 61, no. 6, pp. 2655–2664, Jun. 2014.
- [16] M. S. Irfan, A. Ahmed, and J.-H. Park, "Power-decoupling of a multiport isolated converter for an electrolytic-capacitorless multilevel inverter," *IEEE Trans. Power Electron.*, vol. 33, no. 8, pp. 6656–6671, Aug. 2018.
- [17] K. Sano and M. Takasaki, "A transformerless D-STATCOM based on a multivoltage cascade converter requiring no DC sources," *IEEE Trans. Power Electron.*, vol. 27, no. 6, pp. 2783–2795, Jun. 2012.
- [18] B. Gultekin and M. Ermis, "Cascaded multilevel converter-based transmission STATCOM: system design methodology and development of a 12 kV ± 12 MVar power stage," *IEEE Trans. Power Electron.*, vol. 28, no. 11, pp. 4930–4950, Nov. 2013.
- [19] G. Farivar, B. Hredzak, and V. G. Agelidis, "Reduced-capacitance thin-film H-bridge multilevel STATCOM control utilizing an analytic filtering scheme," *IEEE Trans. Ind. Electron.*, vol. 62, no. 10, pp. 6457–6468, Oct. 2015.
- [20] H. Wang, M. Liserre, and F. Blaabjerg, "Toward reliable power electronics—Challenges, design tools and opportunities," *IEEE Ind. Electron. Mag.*, vol. 7, no. 2, pp. 17–26, Jun. 2013.
- [21] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, "An industry-based survey of reliability in power electronic converters," *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1441–1451, May/Jun. 2011.
- [22] G. Farivar, C. D. Townsend, B. Hredzak, J. Pou, and V. G. Agelidis, "Low-capacitance cascaded H-bridge multilevel StatCom," *IEEE Trans. Power Electron.*, vol. 32, no. 3, pp. 1744–1754, Mar. 2017.
- [23] G. Farivar, C. D. Townsend, B. Hredzak, J. Pou, and V. G. Agelidis, "Passive reactor compensated cascaded H-bridge multilevel LC-StatCom," *IEEE Trans. Power Electron.*, vol. 32, no. 11, pp. 8338–8348, Nov. 2017.
- [24] T. Isobe, D. Shiojima, K. Kato, Y. R. R. Hernandez, and R. Shimada, "Full-bridge reactive power compensator with minimized-equipped capacitor and its application to static var compensator," *IEEE Trans. Power Electron.*, vol. 31, no. 1, pp. 224–234, Jan. 2016.
- [25] T. Isobe, L. Zhang, H. Tadano, J. A. Suul, and M. Molinas, "Control of DC-capacitor peak voltage in reduced capacitance single-phase STATCOM," in *Proc. IEEE 17th Workshop on Control and Modeling for Power Electronics (COMPEL)*, 2016, pp. 1–8.
- [26] Z. He, L. Zhang, T. Isobe, and H. Tadano, "Dynamic performance improvement of single-phase STATCOM with drastically reduced capacitance," in *Proc. IEEE 3rd International Future Energy Electronics Conference and ECCE Asia (IFEEC 2017 and ECCE Asia)*, 2017, pp. 1413–1418.
- [27] G. Farivar, C. D. Townsend, J. Pou, and B. Hredzak, "Low-capacitance StatCom with modular inductive filter," *IEEE Trans. Power Electron.* (Early Access).
- [28] G. Farivar and J. Pou, "LC-StatCom with symmetrical I-V characteristic — power loss analysis," in *Proc. 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe)*, 2017, pp. 1–10.
- [29] G. Farivar, J. Pou, and A. Tripathi "LC-StatCom with symmetrical I-V characteristic — total harmonic distortion study," in *Proc. Asian Conference on Energy, Power and Transportation Electrification (ACEPT)*, Oct. 2017.
- [30] D. Petrili, A. Nami, C. D. Townsend, and H. Z. de la Parra, "Active ripple energy storage for a cascaded H-bridge multilevel converter," in *Proc.*

18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe), Sep. 2016, pp. 1-10.

- [31] Y. Tang, F. Blaabjerg, P. C. Loh, C. Jin and P. Wang, "Decoupling of fluctuating in single-phase systems through a symmetrical half-bridge circuit," *IEEE Trans. Power Electron.*, vol. 30, no. 4, pp. 1855-1865, Apr. 2015.
- [32] K.-H. Chao and P.-T. Cheng, "Power decoupling methods for single-phase three-poles AC/DC converters," in *Proc. IEEE Energy Conversion Congress and Exposition*, Sep. 2009, pp. 3742-3747.
- [33] Y. Cheng, C. Qian, M. L. Crow, S. Pekarek, and S. Atcitty, "A comparison of diode-clamped and cascaded multilevel converters for a STATCOM with energy storage," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1512– 1521, Oct. 2006.
- [34] Z. Yang, M. L. Crow, C. Chen, and L. Zhang, "The steady state characteristics of a StatCom with energy storage," in *Proc. Power Engineering Society Summer Meeting*, vol. 2, pp. 669-674, Jul. 2000.
- [35] M. J. Hossain, H. R. Pota, and R. A. Ramos, "Improved low-voltage-ride-through capability of fixed speed wind turbines using decentralised control of STATCOM with energy storage system," *IET Generation, Transmission & Distribution*, vol. 6, no. 8, pp. 719-730, Aug. 2012.
- [36] F. H. M. Rafi, M. J. Hossain, and J. Lu, "Design of a single stage transformerless VSI in a smart microgrid for PV-STATCOM/ESS operations," in *Proc. Australasian Universities Power Engineering Conference (AUPEC)*, Sep. 2014, pp. 1-6.
- [37] Y. T. Jeon, G. Farivar, C. D. Townsend, J. H. Park, and J. Pou, "Capacitor voltage shaper for cascaded H-bridge STATCOM," in *Proc. 4th IEEE Southern Power Electronics Conference (SPEC)*, Dec. 2018, pp. 78-82.
- [38] R. Alvarez, M. Pieschel, H. Gambach, and E. Spahic, "Modular multilevel converter with short-time power intensive electrical energy storage capability," in *Proc. IEEE Electrical Power and Energy Conference (EPEC)*, Oct. 2015, pp. 131-137.